

Dissociation of Feshbach molecules via spin-orbit coupling in ultracold Fermi gases

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We study the dissociation of Feshbach molecules in ultracold Fermi gases with spin-orbit (SO) coupling. Since SO coupling can induce quantum transition between the Feshbach molecules and the fully polarized Fermi gas, the Feshbach molecules can be dissociated by the SO coupling. We experimentally realized this new type of dissociation in ultracold gases of ^{40}K atoms with SO coupling created by Raman beams, and observed that the dissociation rate is highly non-monotonic on both the positive and negative Raman-detuning sides. Our results show that the dissociation of Feshbach molecules can be controlled by new degrees of freedoms, i.e., the SO-coupling intensity or the momenta of the Raman beams, as well as the detuning of the Raman beams.

Introduction. Recently spin-orbit (SO) coupling has emerged as one of the most exciting research directions in ultracold atom physics. It plays a key role in a variety of systems and gives rise to new phenomena ranging from topological insulators [1–4] to Majorana fermions [5]. Ultracold atomic gases offer an unique platform for engineering synthetic SO coupling due to the wide tunability of experimental parameters. Many schemes of generating artificial Abelian and non-Abelian gauge fields have been developed via atom-light interaction [6–9]. An equal combination of Rashba and Dresselhaus SO coupling was first realized experimentally in a neutral atomic BEC by NIST group [10], in which two atomic spin states are dressed by a pair of counter-propagating laser beams with two-photon Raman transition. Successively, several groups were realized experimentally with the same scheme and studied the intriguing properties of SO-coupled BEC [11–15].

In parallel, SO-coupled Fermi gases [16] have also attracted a great deal of attentions, since SO coupling induces coupling between spin-triplet and spin-singlet states and further gives rise to non-trivial topological order and Majorana fermions. Lots of progresses has been made on the experimental exploration of the SO-coupled Fermi gases. The SO-coupled non-interacting fermionic ^{40}K [17] and ^6Li [18] atoms have been investigated. Subsequently, SO-coupled Fermi gases were studied experimentally near a Feshbach resonance. The SO-coupling-induced shift of the binding energy of a Feshbach molecule has been observed via both radio-frequency spectroscopy [19] and scattering resonance induced by Raman beams [20]. Furthermore, it has been observed that SO coupling can coherently produce s -wave Feshbach molecules from a fully polarized Fermi gas, and induce a coherent oscillation between these two [21].

In this letter, we report that SO coupling can dissociate s -wave Feshbach molecules formed by ultracold

Fermi atoms in different pseudo spin states. In our experiment we prepare Feshbach molecules of ultracold ^{40}K atoms in states $|F = 9/2, m_F = -7/2\rangle (|\uparrow\rangle)$ and $|F = 9/2, m_F = -9/2\rangle (|\downarrow\rangle)$, and then create an SO coupling by ramping up two counter-propagating Raman beams, as in Refs. [10, 17, 18] (Fig. 1(a)). After this ramping process, we measure the number of remaining Feshbach molecules as a function of the Raman detuning of the spin-orbit coupling. We observe that a significant loss of Feshbach molecules is induced by the SO coupling. The maximum loss occurs on both the positive and negative side of the Raman resonance. These observations are consistent with our theoretical analysis. This analysis shows that the loss effect is due to the SO-coupling-induced transition from the Feshbach molecule state, in which the two atoms are in the singlet pseudo spin state, to free-motion states of two atoms in the polarized pseudo spin states $|\uparrow\rangle_1|\uparrow\rangle_2$ or $|\downarrow\rangle_1|\downarrow\rangle_2$. It is quite different from radio-frequency (RF) beam induced dissociation of a Feshbach molecule into two free atoms in the singlet state of different hyperfine states $|\downarrow\rangle$ and $|F = 9/2, m_F = -5/2\rangle$ [23, 25]. Our work demonstrates that SO coupling, as a momentum-dependent Zeeman field, can entangle the two-atom internal state with the relative spatial motion, and thus exhibits significantly different effect on Feshbach molecule, comparing to a momentum independent Zeeman field.

Experiment. Our experimental setup for the preparation of the Feshbach molecules and SO coupling in the ultracold Fermi gas ^{40}K has been described in detail in Refs. [19, 21]. We prepare an equal mixture of 2×10^6 ultracold ^{40}K atoms in the pseudospin states $|\uparrow\rangle$ and $|\downarrow\rangle$, and then adiabatically sweep the magnetic field across the Feshbach resonance point $B_0 = 202.20\text{G}$ (Fig. 1(b)). As a result of this adiabatic sweeping, many pairs of atoms in state $|\uparrow\rangle_1|\downarrow\rangle_2$ are converted into the s -wave Feshbach molecules. The binding energy of the molecules

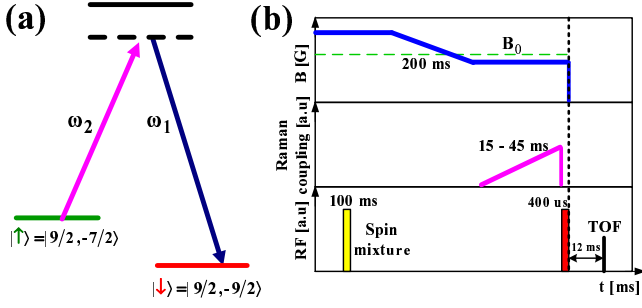


FIG. 1: (Color online). (a) Schematic diagram of SO coupling for ^{40}K . (b) The time sequence of the homogeneous bias magnetic field, the Raman coupling and the RF field. Here $B_0 = 202.2$ G is the Feshbach resonance point of atoms in $|F = 9/2, m_F = -9/2\rangle$ and $|F = 9/2, m_F = -7/2\rangle$.

is determined by the final magnetic field strength in the sweeping process. Subsequently, we apply the SO coupling by switching on a pair of counter-propagating Raman laser beams [10, 17, 18], which effectively couple the states $|\uparrow\rangle$ and $|\downarrow\rangle$ (Fig. 1(a)). The momentum transfer in the Raman process is $2k_r \equiv 4\pi\hbar/\lambda$, where $\lambda = 772.4$ nm is the wavelength of the Raman beams. In our system the two-photon detuning is defined as $\eta = \hbar(\omega_1 - \omega_2 - \omega_Z)$, where $\omega_{1,2}$ are the frequencies of the two Raman beams (Fig. 1(a)), and $\hbar\omega_Z$ is the Zeeman splitting between states $|\uparrow\rangle$ and $|\downarrow\rangle$.

In each experiment, we fix the value of η and ramp the intensity of the Raman coupling from zero to a maximum value, and then switch off the Raman beams (Fig. 1(b)). When the Raman beams are switched off, we measure the number of remaining Feshbach molecules in the trap with the approach in Refs. [19, 21]. We apply an RF pulse with duration about $400 \mu\text{s}$ to dissociate these molecules into free atoms in states $|\downarrow\rangle$ and $|F = 9/2, m_F = -5/2\rangle$, and then measure the number N_j ($j = -7/2, -5/2$) of atoms in $|F = 9/2, m_F = j\rangle$ via time-of-flight technique. The number of remaining molecules is known as $N_{\text{rem}} = N_{-5/2}$, while $N_{\text{tot}} = N_{-5/2} + N_{-7/2}$ is half the number of all the ^{40}K atoms in our system.

In Figs. 2 (c, e, g), we illustrate the ratio $N_{\text{rem}}/N_{\text{tot}}$ between the number of remaining molecules and half the number of all the atoms, as a function of two-photon detuning η . It is clearly shown that in some parameter regions this ratio approaches zero. Therefore, in these regions most of the molecules are dissociated. For comparison, we also do measurements (Fig. 2(a)) in the system where the two Raman beams propagate along the same direction (the other parameters are same as the Fig. 2(c)). In this case, SO coupling cannot be created by the Raman beams, and we find that the ratio $N_{\text{rem}}/N_{\text{tot}}$ is large and does not change with η . Note that the narrow peak in the blue Raman detuning of about $58 E_r$ is due to the bound-to-bound (Feshbach molecular state to deeply bound molecular states) transitions with the

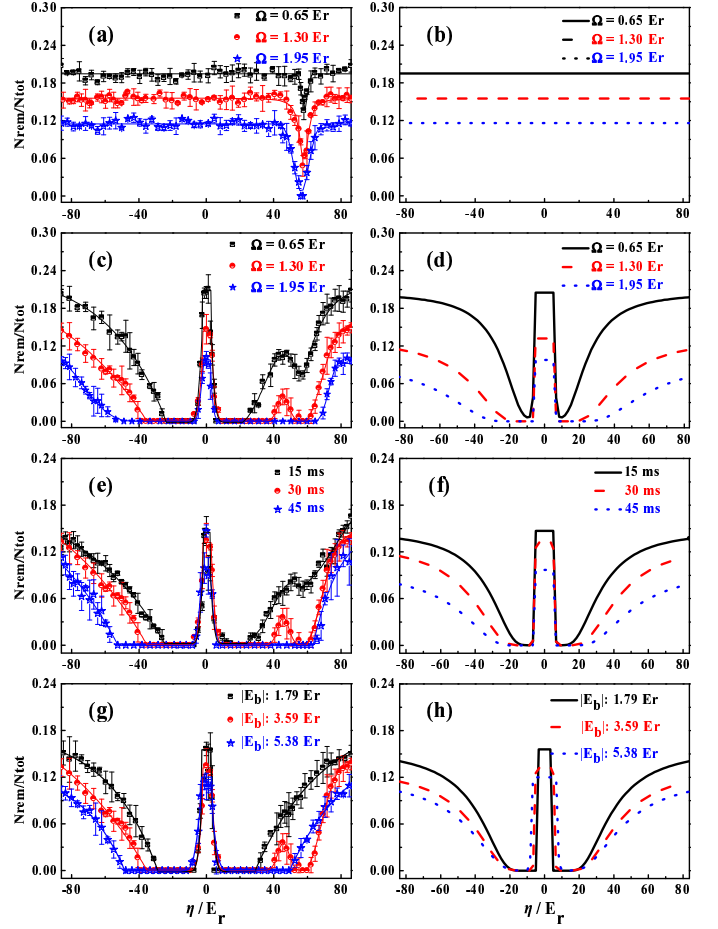


FIG. 2: (Color online). The ratio $N_{\text{rem}}/N_{\text{tot}}$ between the number N_{rem} of remaining Feshbach molecules and half the number N_{tot} of all atoms. Here we illustrate experimental (a, c, e, g) and theoretical (b, d, f, h) results as functions of Raman detuning η . (a) and (b): results without SO coupling (the two Raman beams propagating along the same direction). (c) and (d): results with binding energy of Feshbach molecule $|E_b| = 3.59 E_r$, ramping time $T = 30$ ms, and different values of final intensity Ω of Raman coupling. (e) and (f): results with $|E_b| = 3.59 E_r$, $\Omega = 1.30 E_r$, and different T . (g) and (h): results with $\Omega = 1.30 E_r$, $T = 30$ ms and different $|E_b|$.

Raman lasers [31]. Therefore, in our system the dissociation of the Feshbach molecules is induced by the SO coupling. Below we will give a theoretical explanation for this SO-coupling-induced dissociation. We show that in the presence of SO coupling, the Raman beams can induce a transition from the Feshbach molecule state to the free-motion states of two atoms in $|\uparrow\rangle_1|\uparrow\rangle_2$ or $|\downarrow\rangle_1|\downarrow\rangle_2$. As a result, the molecules can be dissociated. Nevertheless, when there is no SO coupling, this transition is forbidden by the symmetry of the system.

Figures 2 (c, e, g) also show that, when the two-photon detuning η is zero, the ratio $N_{\text{rem}}/N_{\text{tot}}$ remains unchanged compared with the case in which the SO cou-

pling is not applied. Therefore, in that case there is no dissociation effect. Nevertheless, when $|\eta|$ is increased to a sufficient detuning, $N_{\text{rem}}/N_{\text{tot}}$ rapidly decreases, which corresponds to the steep threshold behavior of the dissociation process. In some regions with finite $|\eta|$, $N_{\text{rem}}/N_{\text{tot}}$ is negligible. This implies that in these regions the dissociation effect is very strong and saturated. This phenomenon is due to the energy conservation in the Raman-beam-induced transition. As shown in the theoretical analysis below, when $\eta = 0$, the Feshbach molecule state lies in the lowest energy state of the system and all the polarized states are energetically off-resonant with the Feshbach molecule state. Thus there is no dissociation effect. When the detuning η takes a sufficient positive value, the Feshbach molecule state becomes resonant with the lower free-motion states in $|\uparrow\rangle_1|\uparrow\rangle_2$. As a result, the transitions from the Feshbach molecule state to these states can take place and are strong if η is not too large. We thus can observe a significant dissociation effect and a steep threshold behavior. Similarly, when η reaches a sufficient negative, the Feshbach molecule state becomes resonant with polarized states in $|\downarrow\rangle_1|\downarrow\rangle_2$, and thus dissociation can take place.

Furthermore, as shown in Figs. (c, e, g), in the regions where $|\eta|$ is extremely large, the ratio $N_{\text{rem}}/N_{\text{tot}}$ gradually increases with $|\eta|$. Therefore, in these regions the dissociation effect becomes weak again. According to our theoretical analysis, this is because that the Feshbach molecule state is resonant with free-motion states with high momentum when $|\eta|$ is very large. As a result, the matrix element of the Hamiltonian between these two states (Frank-Condon factor) becomes small, and thus the transition rate from the molecule state to the polarized states is decreased.

We also investigate the dependence of the dissociation effect on other physical parameters. In Fig. 2(c) we illustrate $N_{\text{rem}}/N_{\text{tot}}$ measured with the binding energy of the Feshbach molecule $|E_b| = 3.59E_r$, ramping time $T = 30$ ms, and final intensity of Raman coupling in the ramping process $\Omega = 0.65E_r$, $1.30E_r$ and $1.95E_r$, where $E_r = k_r^2/(2m) = \hbar \times 52.52$ kHz is the recoil energy of the Raman beams. Here m is the single-atom mass. In Fig. 2(e) we show the values of $N_{\text{rem}}/N_{\text{tot}}$ for $|E_b| = 3.59E_r$, $\Omega = 1.30E_r$, and $T = 15$ ms, 30 ms and 45 ms. Our measurements show that the dissociation effect is strong under the condition of long ramping time and high final intensity of Raman coupling. In Fig. 2(g) we illustrate $N_{\text{rem}}/N_{\text{tot}}$ for $T = 30$ ms, $\Omega = 1.30E_r$, and $|E_b| = 1.79E_r$, $3.59E_r$ and $5.38E_r$. We find that the dissociation effect increases with the binding energy $|E_b|$ of the Feshbach molecule (Note that the narrow peak for the bound-to-bound transitions with the Raman lasers is shifted when the magnetic field (binding energy) is changed [31]). This phenomenon can possibly be explained with the following analysis. When $|E_b|$ becomes larger, the Feshbach molecule state has a broader mo-

mentum distribution. As a result, there are more free-motion states which have large overlap (Frank-Condon factor) with the molecule state.

In the following we present a detailed theoretical analysis for our experiment. We theoretically calculate the ratio $N_{\text{rem}}/N_{\text{tot}}$ with the same parameters as our experiments, which agree well with the experimental measurements.

Theoretical analysis. Our experimental results can be qualitatively explained with a simple 2-body analysis. For convenience, here we discuss our problem in the co-moving frame which is related to the original frame via a spin-dependent unitary transformation $\mathcal{U} = e^{-ik_0(x_1\sigma_z^{(1)} + x_2\sigma_z^{(2)})}$, with $\sigma_z^{(i)} = |\uparrow\rangle_i\langle\uparrow| - |\downarrow\rangle_i\langle\downarrow|$ and $k_0 = k_r \sin \frac{\theta}{2}$, where θ is the angle between two Raman beams. In this co-moving frame, the Hamiltonian of the two atoms is $H = H_1 + H_2$, with ($\hbar = m = 1$)

$$H_1 = \sum_{i=1,2} \left[\frac{1}{2} \left(\mathbf{p}^{(i)} + k_0 \sigma_z^{(i)} \mathbf{e}_x \right)^2 - \frac{\eta}{2} \sigma_z^{(i)} \right] + V, \quad (1)$$

$$H_2 = \frac{\Omega}{2} \left(\sigma_x^{(1)} + \sigma_x^{(2)} \right). \quad (2)$$

Here $\mathbf{p}^{(i)}$ ($i = 1, 2$) is the momentum of atom i , \mathbf{e}_x is the unit vector along the x -direction, $\sigma_x^{(i)} = |\uparrow\rangle_i\langle\downarrow| + |\downarrow\rangle_i\langle\uparrow|$, Ω is the Raman-coupling strength. In Eq. (1), V is the inter-atom interaction operator in the co-moving frame. In the low-energy case, we only consider the interaction between fermionic atoms in different pseudo spin states. Based on this model, we can explain our experimental results.

(1) *Finite k_0 is necessary for the dissociation of Feshbach molecule.* According to Eqs. (1) and (2), when the Raman beams are turned on, the pseudospin-dependent part of the total Hamiltonian H of the two atoms can be written as $\mathbf{h}(\mathbf{p}^{(1)})\sigma_1 + \mathbf{h}(\mathbf{p}^{(2)})\sigma_2$, where $\mathbf{h}(\mathbf{p}^{(i)}) = \frac{\Omega}{2} \mathbf{e}_x + p_x^{(i)} k_0 \mathbf{e}_z$ is the effective Zeeman field experienced by atom i . In the system where the two Raman beams propagate along the same direction, we have $k_0 = 0$, and there is no synthetic SO coupling. As a result, the effective field is momentum-independent. Thus, when the Raman beams are applied, the pseudospins of the two atoms rotate along the same axis. Furthermore, the two atoms in the Feshbach molecule are in the singlet state $|S\rangle$, which cannot be changed by such rotation. Therefore, the Raman beams cannot dissociate the Feshbach molecule. On the other hand, when the two Raman beams propagate along different directions, we have $k_0 \neq 0$, and the synthetic SO coupling is induced by the Raman beams. In this case the two atoms with different momentum \mathbf{k}_1 and \mathbf{k}_2 can experience different effective fields $\mathbf{h}(\mathbf{k}_1)$ and $\mathbf{h}(\mathbf{k}_2)$. Thus, the Raman beams can rotate the pseudospins of the two atoms along different axis. Therefore, although the two atoms in the Feshbach molecule are polarized along opposite directions, when the Raman beams are turned on, they have some probability to evolve to the

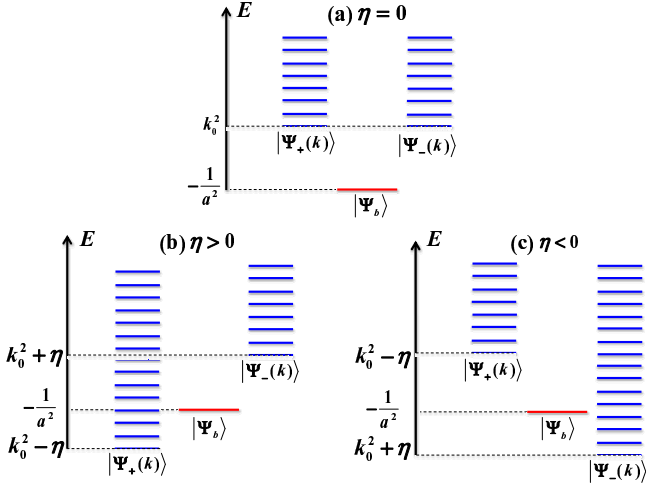


FIG. 3: (Color online) The energy spectrums of eigenstates of H_F with two-photon detuning $\eta = 0$ (a), $\eta > 0$ (b) and $\eta < 0$ (c).

parallel-polarized state where the pseudospins are along the same direction. As a result, the Feshbach molecule can be dissociated by the Raman beams.

This result can also be understood with the following detailed analysis. According to Eqs. (1) and (2), before the Raman beams are applied, we have $\Omega = 0$ and thus $H_2 = 0$. Therefore, the two-atom Hamiltonian in the co-moving frame is H_1 . The atoms are prepared in the Feshbach molecule state. In the original frame, this state is $|\Phi_b\rangle = \int d\mathbf{r}_1 d\mathbf{r}_2 \phi_b(\mathbf{r}) |\mathbf{r}_1\rangle_1 |\mathbf{r}_2\rangle_2 |S\rangle$, where $|S\rangle = (|\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2)/\sqrt{2}$ is singlet state, $|\mathbf{r}_i\rangle_i$ is the eigen-state of the position of the i th atom, $\mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2$ and $\phi_b(\mathbf{r}) = e^{-r/a}/\sqrt{2a\pi}$, with a the scattering length between atoms in states $|\uparrow\rangle$ and $|\downarrow\rangle$. Therefore, in the co-moving frame the Feshbach molecule state is $|\Phi_b^{(C)}\rangle \equiv \mathcal{U}|\Phi_b\rangle$. It is an eigen-state of H_1 , with eigen-energy $E_b = -a^{-2}$.

In the system with $k_0 = 0$, we have $\mathcal{U} = 1$ and thus $|\Phi_b^{(C)}\rangle = |\Phi_b\rangle \propto |S\rangle$. When the Raman beams are turned on, the atom-laser interaction is described by the Hamiltonian H_2 in Eq. (2). Nevertheless, since $H_2|S\rangle = 0$, the Raman beams cannot induce quantum transition from $|\Phi_b^{(C)}\rangle$ to other states. Therefore, the Raman beams cannot dissociate the Feshbach molecule.

When $k_0 \neq 0$, we have $\mathcal{U} \neq 1$. In this case the Feshbach molecule state in the co-moving frame is $|\Phi_b^{(C)}\rangle = \mathcal{U}|\Phi_b\rangle = |\phi_+\rangle|S\rangle + |\phi_-\rangle|T\rangle$, where $|T\rangle = (|\uparrow\rangle_1 |\downarrow\rangle_2 + |\downarrow\rangle_1 |\uparrow\rangle_2)/\sqrt{2}$ is triplet state, and $|\phi_\pm\rangle = \frac{1}{2} \int d\mathbf{r}_1 d\mathbf{r}_2 [\phi_b(\mathbf{r}) e^{-ik_0 \mathbf{e}_x \cdot \mathbf{r}} \pm \phi_b(\mathbf{r}) e^{ik_0 \mathbf{e}_x \cdot \mathbf{r}}] |\mathbf{r}_1\rangle_1 |\mathbf{r}_2\rangle_2$. It is clear that $H_2|\Phi_b^{(C)}\rangle \propto H_2|T\rangle \propto (|\uparrow\rangle_1 |\uparrow\rangle_2 + |\downarrow\rangle_1 |\downarrow\rangle_2)$. Therefore, when the Raman beams are turned on, the atom-laser interaction H_2 can induce quantum transition from the Feshbach molecule state $|\Phi_b^{(C)}\rangle$ to other eigenstates of H_1 , and thus dissociate the Feshbach molecules.

(2) *Non-monotonic dependence of dissociation on de-*

tuning η . Now we consider the dependence of the dissociation effect on the two-photon detuning η . As shown above, the dissociation is due to Raman-beams-induced transition from the Feshbach molecule state $|\Phi_b^{(C)}\rangle$. With direct calculation, we find that in the first-order processes the final states of these transitions are $|\Psi_+(\mathbf{k})\rangle = |\uparrow\rangle_1 |\uparrow\rangle_2 (|\mathbf{k}\rangle_1 - |\mathbf{k}\rangle_2 - |-\mathbf{k}\rangle_1 |\mathbf{k}\rangle_2)/\sqrt{2}$ and $|\Psi_-(\mathbf{k})\rangle = |\downarrow\rangle_1 |\downarrow\rangle_2 (|\mathbf{k}\rangle_1 - |\mathbf{k}\rangle_2 - |-\mathbf{k}\rangle_1 |\mathbf{k}\rangle_2)/\sqrt{2}$, where $|\mathbf{k}\rangle_i$ is the eigen-state of the momentum of atom i . $|\Psi_\pm(\mathbf{k})\rangle$ are eigen-states of H_1 , with corresponding eigen-energies $E_\pm(\mathbf{k}) = |\mathbf{p}|^2 + k_0^2 \mp \eta$.

Significant quantum transitions can occur between $|\Phi_b^{(C)}\rangle$ and the resonant final states $|\Psi_\pm(\mathbf{k})\rangle$, which satisfies the resonance condition $E_\pm(\mathbf{k}) = E_b = -a^{-2}$. Since $E_\pm(\mathbf{k}) \geq k_0^2 \mp \eta$, when the two-photon detuning $\eta = 0$, this resonance condition cannot be satisfied by any value of \mathbf{k} (Fig. 3(a)). As a result, the dissociation is very weak, and the number of remaining molecules is large. When the two-photon detuning η is increased so that $\eta \gtrsim k_0^2 + 1/a^2$, $|\Phi_b^{(C)}\rangle$ becomes resonant with free motion states $|\Psi_+(\mathbf{k})\rangle$ (Fig. 3(b)). These states have relatively small momentum \mathbf{k} , and thus have large overlap with the Feshbach molecule state (i.e., large Frank-Condon factor). Thus, the transitions from $|\Phi_b^{(C)}\rangle$ to these states are significant. Similarly, when η is tuned to be negative and $-\eta \gtrsim k_0^2 + 1/a^2$, $|\Phi_b^{(C)}\rangle$ becomes resonant with $|\Psi_-(\mathbf{k})\rangle$ with small \mathbf{k} (Fig. 3(c)) and thus the transitions to these states are strong. Therefore, for the cases with either positive or negative η , when the condition $|\eta| \gtrsim k_0^2 + 1/a^2$ is satisfied, the dissociation becomes significant and the ratio $N_{\text{rem}}/N_{\text{tot}}$ between the number of remaining Feshbach molecules and half the number of all the atoms becomes very small. In addition, when $|\eta|$ is further increased so that $|\eta| \gg k_0^2 + 1/a^2$, $|\Phi_b^{(C)}\rangle$ is resonant with states $|\Psi_\pm(\mathbf{k})\rangle$ with very large \mathbf{k} . As a result, the overlap of the molecule state and $|\Psi_\pm(\mathbf{k})\rangle$ becomes very small. Thus, the dissociation rate is decreased and $N_{\text{rem}}/N_{\text{tot}}$ is increased in the region with large $|\eta|$. As shown in Fig. 2(a, c, e, g), all these effects are observed in our experiment.

Based on the analysis above, we phenomenologically calculate the ratio $N_{\text{rem}}/N_{\text{tot}}$ with Fermi's golden rule (FGR) [32]. We perform the calculations with the same parameters as in the experiments of Fig. 2(a, c, e, g), and illustrate our results in Fig. 2(b, d, f, h). It is clear that our theoretical result is qualitatively consistent with the experimental measurements.

Summary. In summary, we experimentally and theoretically investigate the dissociation effect of Feshbach molecules in the presence of SO coupling. This dissociation effect is due to the SO-coupling-induced transition from the Feshbach molecule state with atoms in the singlet pseudo spin state to free-motion states of two atoms in polarized pseudospin states. This work demonstrates that SO-coupling in a Fermi gas constitutes a new disso-

ciation tool for Feshbach molecules.

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 [32] Our supplementary materials.

SUPPLEMENTARY MATERIAL

phenomenological calculation of the number of remaining molecules

In this supplementary material we show our phenomenological numerical calculation based on Fermi's golden rule (FGR). According to the FGR, for a fixed value of the Rabi frequency, the rate of molecule-atom transition is

$$A[\Omega, \eta] = \pi |\Omega|^2 \int d\mathbf{k} |g_+(\mathbf{k})|^2 \delta \left(|\mathbf{k}|^2 + k_0^2 - \eta + \frac{1}{a^2} \right) + \pi |\Omega|^2 \int d\mathbf{k} |g_-(\mathbf{k})|^2 \delta \left(|\mathbf{k}|^2 + k_0^2 + \eta + \frac{1}{a^2} \right), \quad (3)$$

where

$$g_{\pm}(\mathbf{k}) = \frac{1}{2} \langle \Psi_{\pm}(\mathbf{k}) | [\sigma_x^{(1)} + \sigma_x^{(2)}] | \Phi_b^{(C)} \rangle. \quad (4)$$

Since in our system the total momentum of the two atoms is conserved, here the calculation $\langle \Psi_{\pm}(\mathbf{k}) | [\sigma_x^{(1)} + \sigma_x^{(2)}] | \Phi_b^{(C)} \rangle$ is done in the Hilbert space for the pseudospins and relative spatial motion of the two atoms. It is pointed out that the direct calculation gives $g_+(\mathbf{k}) = g_-(\mathbf{k})$, and thus $r(\eta) = r(-\eta)$. In our experiment the Rabi frequency is ramped from 0 to the maximum value Ω_m during the ramping time T , i.e., we have $\Omega(t) = \Omega_m t/T$. Therefore, in our calculation we use the phenomenological equation

$$\frac{dF(t)}{dt} = -A[\Omega(t), \eta] F(t) \quad (5)$$

to describe the variation of the ratio $F(t) \equiv N(t)/N_{\text{tm}}$ with time t . Here N_{tm} is the total number of the Feshbach molecules created in our system. It is related to half the number N_{tot} of all the atoms with the relation

$$N_{\text{tm}} = N_{\text{tot}} r_P, \quad (6)$$

with r_P the production rate of Feshbach molecule in our experiment. $N(t)$ is the molecule number at time t , and satisfies $N(0) = N_{\text{tm}}$. According to this equation, after ramping Raman beams, the fraction of remaining Feshbach molecules is

$$\frac{N(T)}{N_{\text{tm}}} = F(T) = \exp \{-A[\Omega_m, \eta]T/3\}, \quad (7)$$

with T the ramping time. Furthermore, the number N_{rem} of the remaining molecules detected in our experiment

can be expressed as $N_{\text{rem}} = N(T)r_D$, with r_D the detection rate. Using this relation and Eq. (6), we find that the ratio $N_{\text{rem}}/N_{\text{tot}}$ detected in the experiment is

$$\frac{N_{\text{rem}}}{N_{\text{tot}}} = \frac{N(T)}{N_{\text{tm}}} r_P r_D. \quad (8)$$

Substituting Eq. (7) into Eq. (8), we finally obtain

$$\frac{N_{\text{rem}}}{N_{\text{tot}}} = \exp \{-r[\Omega_m, \eta]T/3\} r_P r_D. \quad (9)$$

In our calculation we take $r_P r_D$ as a single fitting parameter, and determine the value of this parameter by fitting the molecule fraction in the case $\eta = 0$ given by calculation and experimental measurement.